

UH-511-834-95

SUPERSYMMETRY PHENOMENOLOGY: A MICROREVIEW ^a

XERXES TATA

*Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822,
USA*

We briefly review the current status and future prospects for supersymmetry searches at colliders, and discuss strategies by which further information about sparticle properties may be obtained at the LHC.

1 Current Status of Supersymmetry

Direct Constraints from Colliders: There is no evidence for the production of sparticles in high energy collisions. Direct searches¹ for sparticles in experiments at LEP yield lower bounds ~ 45 GeV on the masses of charginos (W_1), charged sleptons and squarks. While these bounds are sensitive to how sparticles decay, the corresponding limits² (which also apply to $m_{\tilde{\nu}}$) from the Z line shape³ (*i.e.* from the measured values of Γ_Z and Γ_Z^{inv}) which are only slightly weaker, are insensitive to specific sparticle decay patterns. Furthermore, since virtual effects of sparticles rapidly decouple as $m_{SUSY} \rightarrow \infty$, the agreement³ of precision measurements at LEP with Standard Model (SM) expectation can be readily accommodated if sparticles are heavier than about 200 GeV: by the same token, if say chargino-top squark loop effects are assumed to be responsible for the deviation in R_b , these should probably be discoverable⁴ at LEP2, or from an analysis⁵ of the data from the current Tevatron run. The quoted value of R_c is more difficult⁶ to accommodate. The best limits on gluinos and squarks come from experiments at hadron colliders. The non-observation of an excess of \cancel{E}_T events has enabled the D0 and CDF experiments to infer⁷ a limit of 173 GeV (229 GeV) on the mass of the gluino if squarks are very heavy (for $m_{\tilde{q}} = m_{\tilde{g}}$). We should not be discouraged by the absence of SUSY signals in current experiments which have probed masses up to 50 GeV (200 GeV) for weakly (strongly) interacting sparticles. In comparison, the natural mass scale for sparticles is 100-1000 GeV in order for supersymmetry to be able to stabilize the elementary scalar sector thought to be responsible for electroweak symmetry breaking.

Framework for SUSY Analysis: The minimal supersymmetric model (MSSM) with no other assumptions other than the particle content, the low energy sym-

^aPresented at the 1995 European Physical Society Meeting, Brussels, Belgium, July 1995.

metry group, and R -parity conservation, leads to a plethora of new parameters (especially in the soft-SUSY breaking sector where we parametrize our ignorance about the physics of SUSY breaking), making phenomenological analyses intractable. For this reason, most analyses today are done within the minimal supergravity (SUGRA) GUT framework⁸ with the radiative breaking of electroweak symmetry. The assumed symmetries about the physics at the high scale then ensure that all sparticle masses and couplings are fixed by just four parameters: a common soft SUSY breaking mass m_0 for all scalars, a common SUSY breaking gaugino mass $m_{1/2}$, a common value (A_0) for trilinear scalar couplings and $\tan\beta$, the ratio of the VEVs of the two Higgs fields in the model. There is some ambiguity about exactly what the scale (M_X), at which the running scalar masses and A -parameters unify, is. We take M_X to be the scale M_{GUT} at which the gauge couplings unify. If $M_X > M_{GUT}$, as it might well be, the scalar masses and A -parameters would not be exactly universal at M_X . The biggest impact of this would probably be on the condition of radiative symmetry breaking⁹ which fixes the superpotential Higgsino mass (μ) squared (notice that the sign of μ is not fixed). Allowing μ to be a free parameter would be tantamount to relaxing this latter constraint. We stress that the assumptions underlying the SUGRA GUT framework may ultimately prove to be incorrect. It is, therefore, important to devise ways by which these might be tested in future experiments, as well as to examine the sensitivity of various signals to these assumptions, particularly when trying to determine the capabilities of future facilities.

2 Sparticle Searches at Future Colliders

The LEP collider will soon enter its second phase and its energy will ultimately be upgraded to 175-200 GeV. Given a data sample of $\sim 300 \text{ pb}^{-1}$, the clean environment of e^+e^- collisions should make it possible to search¹⁰ for charginos, sleptons, squarks, and even Higgs bosons, up to 80-90 GeV (b -tagging capability may be needed if $m_H \simeq M_Z$). The corresponding mass reach for neutralinos is sensitive to their (parameter-dependent) mixing angles. An analysis within the SUGRA framework, where various cross sections are correlated, has also been performed¹¹.

The CDF and D0 experiments have each already accumulated an integrated luminosity of about 100 pb^{-1} . With a sample of this size, they will be able to substantially extend^{12,13} their search for gluinos and squarks in the \cancel{E}_T channel. Moreover, they should also be able to begin searching for multilepton events¹⁴ from their cascade decays: the most promising of which are the same-sign (SS) isolated dileptons plus jets plus \cancel{E}_T and the isolated

trileptons plus jets plus \cancel{E}_T events. The SM *physics* backgrounds in these channels are tiny so that a conclusive observation of even a handful of events in these channels could signal new physics. Although the cross sections for these spectacular signatures is small, these rate-limited channels may already begin to be competitive with the background-limited \cancel{E}_T channel with a reach around 200 GeV (250-300 GeV) if squarks are heavy (if $m_{\tilde{q}} = m_{\tilde{g}}$) by the time this data is analysed. At the Main Injector (MI), where we expect an order of magnitude larger data sample, SUSY searches via these multilepton channels will be very important.

Tevatron experiments should also be able to search¹⁵ for the direct production of charginos and neutralinos (\tilde{Z}_i). The most promising channel is $p\bar{p} \rightarrow \tilde{W}_1 \tilde{Z}_2 \rightarrow \ell\nu\tilde{Z}_1 + \ell'\bar{\ell}'\tilde{Z}_1$, which leads to spectacular events with three, hard isolated leptons and \cancel{E}_T and essentially no jet activity. In fact, the preliminary analyses⁷ of the Run IA data already yield lower bound on $m_{\tilde{W}_1}$ competitive with those from LEP. Assuming the unification of gaugino masses, Tevatron experiments should be able to (indirectly) probe^{16,13} gluino masses up to 400-500 GeV (550-700 GeV) at the MI (TeV33) upgrades for favourable ranges of parameters. Confirmatory signals from chargino pair production may also be present¹⁶. There are, however, regions of parameter space where the branching fraction for the leptonic decay of \tilde{Z}_2 is strongly suppressed so that there is no observable 3ℓ signal^{16,13} even if the chargino is at its current bound from LEP.

Experiments at the Tevatron should also be able to search for the less massive of the two top squarks (\tilde{t}_1) which, because of its large Yukawa interaction, can be substantially lighter than all other squarks even within the SUGRA framework. If \tilde{t}_1 is heavy enough it will dominantly decay via $b\tilde{W}_1$: since the chargino decays via $\tilde{W}_1 \rightarrow f\bar{f}'\tilde{Z}_1$, signals from $\tilde{t}_1\bar{\tilde{t}}_1$ production will then be identical to those from top quark pair production. If the chargino decay mode of \tilde{t}_1 is kinematically inaccessible, it decays¹⁷ via $\tilde{t}_1 \rightarrow c\tilde{Z}_1$ so that top squark pair production is then signalled by multi-jet plus \cancel{E}_T events. It has been shown⁵ that, irrespective of how \tilde{t}_1 decays, with an integrated luminosity of $\sim 100\text{ pb}^{-1}$, experiments at the Tevatron should be able to find it if $m_{\tilde{t}_1} \lesssim 100\text{ GeV}$ (some b -tagging capability is needed for the detection of a leptonically decaying top squark in the $1\ell + jets + \cancel{E}_T$ channel). Indeed a preliminary analysis by the D0 Collaboration¹⁸ excludes $60\text{ GeV} \lesssim m_{\tilde{t}_1} \lesssim 100\text{ GeV}$ if $m_{\tilde{Z}_1} \lesssim 30\text{ GeV}$, and \tilde{t}_1 decays via $\tilde{t}_1 \rightarrow c\tilde{Z}_1$. A recent analysis¹³ suggests that MI experiments should be able to detect a t -squark up to 160 GeV if it decays via the chargino mode. Finally, it has been shown¹⁹ that it difficult to search for sleptons much heavier than 50 GeV even at the MI upgrade of the

Tevatron.

Gluino and squark searches at the LHC are discussed by Polesello²⁰, so we will limit ourselves to simply stating that experiments there should be able to detect²¹ gluinos as heavy as 1300 GeV (2 TeV) if the squark is heavy ($m_{\tilde{q}} = m_{\tilde{g}}$) in the \cancel{E}_T channel. A reach of about 1 TeV should also be possible^{22,21,23} via the SS and multilepton channels. The \cancel{E}_T ²⁴ and leptonic²⁵ signals have been studied within the SUGRA framework: the largest reach is via the 1ℓ channel. It also appears that there is no window of masses where gluinos will evade detection both at the LHC and at the MI. What about other sparticles? LHC experiments should be able to discover sleptons^{26,19} with masses up to about 250 GeV in the $\ell^+\ell^- + \cancel{E}_T$ channel, provided jets can be vetoed with high efficiency to eliminate backgrounds from $t\bar{t}$ production. It should also be possible to search for trileptons²⁷ from $\widetilde{W}_1\widetilde{Z}_2$ production except in those parameter ranges where the leptonic decay of \widetilde{Z}_2 are strongly suppressed. This signal sharply cuts off if \widetilde{Z}_2 is heavy enough to decay into real Z or Higgs bosons. The reach of the Tevatron and its upgrades and the LHC are compared in a recent phenomenological review²⁸.

Discovering charged sparticles (also Higgs bosons) with masses essentially all the way to the beam energy is easy²⁹ at a linear e^+e^- colliders, provided sufficient integrated luminosity is attained (10-30 fb^{-1} at $\sqrt{s} = 500$ GeV). We stress here that the experiments at Tevatron upgrades (including TeV33), while very interesting, cannot explore the complete parameter space of weak scale SUSY. For this, the LHC or a Linear Collider with $\sqrt{s} = 500$ -1000 GeV are essential.

3 Beyond Sparticle Searches

Fujii²⁹ has described how the precision measurements of sparticle masses that can be made with polarized beams at Linear Colliders can be used to incisively test the assumptions underlying the SUGRA GUT framework. At these machines, one would also be able to check³⁰ (to within $\sim 30\%$) whether sparticle couplings are related to the known particle couplings as predicted by SUSY. Here, we will briefly discuss what other interesting things LHC experiments might be able to do if SUSY is discovered.

Mass Measurements: For a wide range of parameters, it is possible to isolate $\ell^+\ell^-\ell'$ events from $\widetilde{W}_1\widetilde{Z}_2$ production from SM as well as other SUSY sources: thus, the end point of the $m(\ell^+\ell^-)$ distribution yields²⁷ a reliable measure of $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$. By using suitable cuts, it is possible to obtain hemispheric separation between the decay products of the two gluinos in the \cancel{E}_T sample from gluino pair production: the mass of the hadronic system in each

hemisphere measures²⁴ $m_{\tilde{g}}$ to 15-25% provided $m_{\tilde{g}} \lesssim 700$ GeV. A similar strategy had been suggested earlier³¹ for same sign dilepton events from gluino pair production, but just one production and decay chain was examined, and that, at the parton level.

Testing SUGRA Assumptions: This is more difficult at hadron colliders. However, because the model is specified by just four parameters plus a sign, various signals become correlated. Since most sparticles should be accessible at the LHC, it would be interesting to see if the various signals there (as well as any signals in LEP2 or Tevatron experiments) can be accounted for by a single set of parameters.

Identifying Sparticle Sources: Since several sparticles will simultaneously be produced at the LHC, it is necessary to identify observables or cuts to separate out these various production mechanisms. Trileptons from $\tilde{W}_1\tilde{Z}_2$ production²⁷ and dileptons from slepton production²⁵ can be isolated by suitable choices of cuts. It should also be possible to tell whether or not squarks are being produced along with gluinos. The presence of squarks in significant numbers will be signalled by a charge asymmetry ($n(\ell^+\ell^+) > n(\ell^-\ell^-)$) in the SS dilepton sample^{22,21}, and also by a somewhat lower jet multiplicity (compared to expectations for the measured gluino mass) in the \cancel{E}_T sample²⁴ than expected from just gluino production. An excess of like-flavour $\ell^+\ell^-$ pairs as compared to $e^\pm\mu^\mp$ pairs would signal³² a significant production of neutralinos in cascade decays. Finally, for some ranges of parameters, it is also possible²⁴ to search for Higgs bosons from cascade decays of gluinos via a bump in the $m_{b\bar{b}}$ distribution in the SUSY-enriched \cancel{E}_T sample.

4 Acknowledgments

Collaboration with H. Baer, M. Bisset, M. Brhlik, C-H. Chen, M. Drees, J. Feng, C. Kao, R. Munroe, H. Murayama, M. Nojiri, F. Paige, M. Peskin, J. Sender and J. Woodside as well as discussion with them and many other colleagues are gratefully acknowledged. This research was supported in part by the U.S. Department of Energy grant DE-FG-03-94ER40833.

References

1. L. Montanet *et. al.* *Phys. Rev.* **D50** (1994) 1173.
2. See *e.g.* H. Baer, M. Drees and X. Tata, *Phys. Rev.* **D41** (1990) 3414.
3. A. Olchevski, *these Proceedings*.
4. J. Wells, C. Kolda and G. Kane, *Phys. Lett.* **B338** (1994) 219.
5. H. Baer, J. Sender and X. Tata *Phys. Rev.* **D50** (1994) 4517.
6. D. Garcia and J. Sola, *Phys. Lett.* **B354** (1995) 335.

7. L. Nodulman, *these proceedings*.
8. M. Drees and S. Martin in *Electroweak Symmetry Breaking and New Physics at the TeV Scale*, T. Barklow, S. Dawson, H. Haber and J. Siegrist, Editors (World Scientific, to be published) MAD/PH-95-879 (1995).
9. M. Olechowski and S. Pokorski, *Phys. Lett.* **B344** (1995) 201; N. Polonsky and A. Pomarol, *Phys. Rev.* **D51** (1995) 6532.
10. M. Chen, C. Dionisi, M. Martinez and X. Tata, *Phys. Rep.* **159** (1988) 201.
11. H. Baer, M. Brhlik, R. Munroe and X. Tata, UH-511-829-95, *Phys. Rev.* **D** (in press).
12. T. Kamon, J. Lopez, P. McIntyre and J. T. White, *Phys. Rev.* **D50** (1994) 5676.
13. S. Mrenna and G. Kane, G. D. Kribbs and J. D. Wells, Cal Tech preprint, CALT-68-1986 (1995).
14. H. Baer, C. Kao and X. Tata, *Phys. Rev.* **D51** (1995) 2180.
15. R. Arnowitt and P. Nath, *Mod. Phys. Lett.* **A2** (1987) 331; H. Baer and X. Tata, *Phys. Rev.* **D47** (1993) 2739; H. Baer, C. Kao and X. Tata, *Phys. Rev.* **D48** (1993) 5175.
16. H. Baer, C-H. Chen, C. Kao and X. Tata, *Phys. Rev.* **D52** (1995) 1565.
17. K. Hikasa and M. Kobayashi, *Phys. Rev.* **D36** (1987) 724.
18. J. Wightman, *these Proceedings*.
19. H. Baer, C-H. Chen, F. Paige and X. Tata, *Phys. Rev.* **D49** (1994) 3283.
20. G. Polesello, *these Proceedings*.
21. ATLAS Technical Proposal, CERN/LHCC/94-43 (1994).
22. H. Baer, X. Tata and J. Woodside, *Phys. Rev.* **D45** (1992) 142; H. Baer, M. Bisset, X. Tata and J. Woodside, *Phys. Rev.* **D46** (1992) 303.
23. M. Guchait and D. P. Roy, *Phys. Rev.* **D52** (1995) 133.
24. H. Baer, C-H. Chen, F. Paige and X. Tata, *Phys. Rev.* **D52** (1995) 2746.
25. H. Baer, C-H. Chen, F. Paige and X. Tata (in preparation).
26. F. del Aguila and Ll. Ametller, *Phys. Lett.* **B261** (1991) 326.
27. H. Baer, C-H. Chen, F. Paige and X. Tata, *Phys. Rev.* **D50** (1994) 4508.
28. H. Baer *et. al.*, Ref. ⁸
29. K. Fujii, *these Proceedings*. See also, K. Fujii, H. Murayama, M. Yamaguchi and Y. Okada, *Phys. Rev.* **D51** (1995) 3153.
30. J. Feng, H. Murayama, M. Peskin and X. Tata, *Phys. Rev.* **D52** (1995) 1418.
31. R. M. Barnett, J. Gunion and H. Haber, *Phys. Lett.* **B315** (1993) 349.
32. H. Baer, M. Drees, C. Kao, M. Nojiri and X. Tata, *Phys. Rev.* **D50** (1994) 2148.